

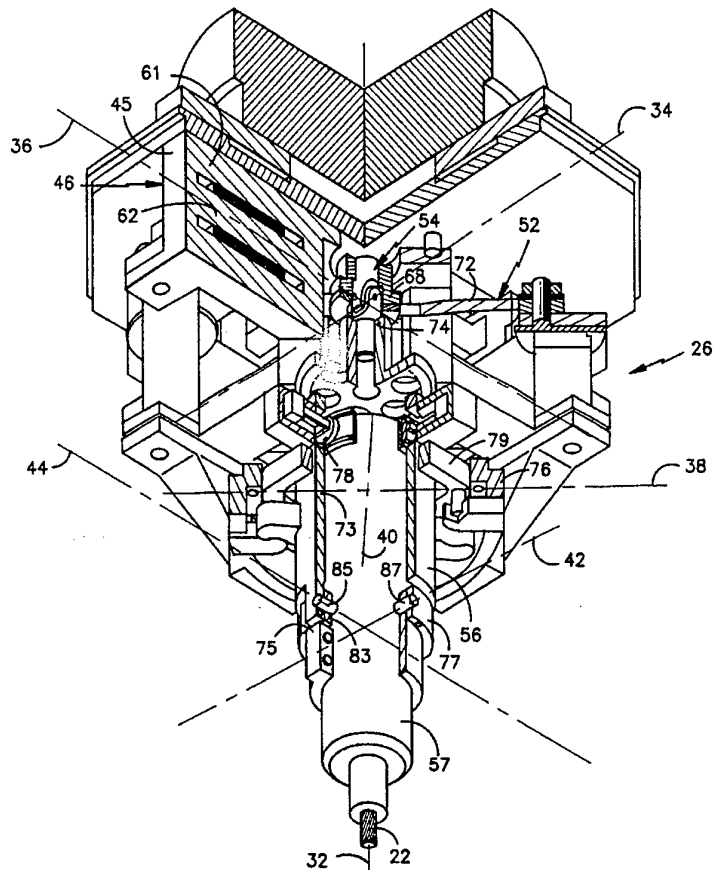
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<p>(21) International Application Number: PCT/US94/10091</p> <p>(22) International Filing Date: 9 September 1994 (09.09.94)</p> <p>(30) Priority Data:</p> <table border="0"> <tr> <td>120,262</td> <td>13 September 1993 (13.09.93)</td> <td>US</td> </tr> <tr> <td>171,891</td> <td>22 December 1993 (22.12.93)</td> <td>US</td> </tr> </table> <p>(71) Applicant: UNITED TECHNOLOGIES CORPORATION [US/US]; United Technologies Building, Hartford, CT 06101 (US).</p> <p>(72) Inventors: ENGEL, Thomas, W.; 635 South Main Street, Manchester, CT 06040 (US). ROBERTS, Randall; 48 Settlement Road, Amston, CT 06231 (US). DOLD, Robert, H.; 678 Main Street, Agawam, MA 01001 (US). KETTLE, John, L.; 3 Bruce Drive, Vernon, CT 06066 (US). MEZEL, Steve, J.; 34 Pilgrim Drive, Tolland, CT 06084 (US).</p> <p>(74) Agent: HENLEY, Randy, G.; United Technologies Corporation, Pratt & Whitney, 400 Main Street, East Hartford, CT 06108 (US).</p>		120,262	13 September 1993 (13.09.93)	US	171,891	22 December 1993 (22.12.93)	US	<p>(81) Designated States: AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DE (Utility model), DK, ES, FI, GB, HU, JP, KP, KR, KZ, LK, LU, LV, MG, MN, MW, NL, NO, NZ, PL, PT, RO, RU, SD, SE, SK, UA, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).</p> <p>Published <i>Without international search report and to be republished upon receipt of that report.</i></p>
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(54) Title: FORCE AND POSITION CONTROLLED MANIPULATOR

(57) Abstract

A manipulator (26) for controlling force and position of a retained device (22) is disclosed. Various construction details are disclosed that provide a manipulator (26) which is back driveable and which provides planar control of both force and position of the device relative to an object being worked on. In a particular embodiment, the manipulator (26) includes an actuator assembly (46) having two pairs of voice coils (58, 59), a housing (56) gimbaled to a frame (45) and engaged with the actuator assembly (46) through a universal joint (54), and a tool (22) retained in a distal end of the housing (56). Excitation of the voice coils (58, 59) produces a planar force on the joint (54). Movement of the joint (54) results in pivoting of the housing (56) about the gimbal (76) and spherical motion of the device. In a further embodiment, the manipulator (26) includes a body (57) gimbaled to the housing (56) and a plurality of force transducers (82) disposed about the body (57) and between the body (57) and housing (56). Forces on the device may be measured by the response of the transducers (82). In another embodiment, the manipulator (26) includes a plurality of position sensors (114, 116) disposed about the gimbal (76) and between the housing (56) and frame (45). The plurality of position sensors (114, 116) respond to pivoting motion of the housing (56) such that the position of the device (22) may be monitored.



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Force and Position Controlled Manipulator

Description

Technical Field

This invention relates to manipulators and, more specifically, to manipulators which provide position and force control for a manipulated device relative to an object being worked upon by the device.

Although the invention was developed in the field of robotics and robotically controlled tools, it has application in other fields in which force control, force measurement, position control or position measurement of a controlled device is required.

Background of the Invention

Manual deburring of manufactured parts is a time consuming, inconsistent and costly step in the manufacturing process. For precision manufacturing of aerospace components, manual deburring consumes as much as 12% of the total machining hours. In addition, there are health costs associated with the manual performance of repetitive tasks. Repetitive motion disorders, such as Carpal Tunnel Syndrome, are some of the health problems that may be related to manual deburring.

Not too surprisingly, automating the deburring process has received much attention but with limited success. Both robotically controlled deburring and deburring using numerically controlled machines has been attempted. Problems associated with automation include achieving and maintaining an accurate tool path, accommodating unexpected deviations in the surface of the part to be machined,

maintaining a constant cutting force, accommodating wear of the cutting tool, adapting to large burrs, and having a repeatable process.

5 One source of accuracy problems is the robot arm itself. In a type of control referred to as "through the arm" control, the robot arm is used to position and provide force for the device. An example of this type of control is described in a report entitled "Force-Controlled Robotic Deburring" authored by Corke et al. Robotic arms however,
10 lack the stiffness and positioning resolution required to precisely control the path of the tool or device. One way around this problem is to use an arrangement known as "around the arm" control. In this arrangement, the arm of the robot is used for gross positioning of the tool and a
15 manipulator, attached to the end of the robot arm, is used for precise manipulation of the tool. An example of this type of control is described in a report entitled "Robotic Force Control for Deburring using an Active End Effector" authored by Bone & Elbestawi.

20 There are several methods of "around the arm" control. One method is to control the position of the tool relative to the object being worked on, either by programming in a set path for the tool or by positioning the tool in response to the object. Either way, a significant drawback
25 to using position control is the lack of compliance in the direction of force applied between the tool and the object. Compliance is necessary to accommodate unexpected deviations in the surface of the object or programmed in path errors. Without compliance, these deviations can
30 produce a sudden fluctuation in the working force on the tool and result in inconsistent results or damage to the tool or the object.

Another method of "around the arm" control is known as

force control. In this method, the force between the tool and the object is controlled to be at or near a predetermined working force. There are two well known methods of accomplishing force control. The first is passive force control. This typically involves using either a spring and damper arrangement or a pneumatic pressure accumulator to maintain a relatively constant, one-dimensional working force on the object, typically in a direction normal to the edge or surface being worked on. Compliance in only one direction, i.e. the direction of the working force or normal direction, is inherent to both of these types of passive force control. Examples of both types of passive force control are described in the following U.S. patents: Patent No. 4,637,775 issued to Kato; Patent No. 4,784,540 issued to Underhaug; and Patent No. 4,860,500 issued to Thompson. Limitations to this type of control include the inability to maintain precise forces on the tool and the one-dimensional nature of the passive control.

The second type of force control is referred to as active force control. In this type of control, the force on the tool is maintained at a constant level by an actuation and sensing system. An example of such a force control is described in the previously discussed report by Bone and Elbestawi. The type of force control described therein included a motor, a ball screw unit which converts the rotary motion of the motor to linear motion, a contact force sensing system, and a body or housing which pivots in response to the linear motion of the ball screw. The transmissions necessary for converting rotary motion to linear and then to angular compromise the accuracy and dynamics of the control because of stiction and backlash. In addition, the transmissions provide minimal or no

passive back driveability.

"Back driveability" is defined herein as the ability of the tool or device to move or be moved without the active aid of the servo-system for the tool. The tool or device can be moved in response to an external force without the need of the servo-system being active. A typical external force is a large burr or an unexpected deviation in the surface being worked on. In active non-back driveable force control systems, the actuation system must be actively back driven in response to force variations and therefore requires a high bandwidth feedback loop to sense the force fluctuations and trigger the actuation system to respond.

In active force control a hybrid position/force control may be used, such as described in a report by Hollowell entitled "Hybrid Force/Position Control for Robotic Light Machining". In this type of control, position is controlled in one direction, tangential to the surface or edge of the object, and force is controlled in another direction, normal to the surface or edge and perpendicular to the position direction.

There are several limitations to the known types of active force controls. One is response time. The active control must sense the fluctuation in force and respond to it by varying the force on the tool. If the response is too slow, damage to the tool or object may result. High bandwidth feedback loops are required to minimize the response time of the active force control. Unfortunately, the achievable bandwidth of non-back drivable actuation systems is severely limited by the presence of relatively low frequency resonant dynamic modes of commercial industrial robot arms. The high bandwidths necessary with non-back driveable actuation systems have extended into the

range of the resonant frequencies of the robot arms. In this situation, excitation of the robot arm resonance can result in control problems due to the unstable nature of the arrangement.

5 The above art notwithstanding, scientists and engineers under the direction of Applicants' Assignee are working to develop manipulators for robotics arms or other forms of programmable position controllers that provide back driveability while maintaining accuracy of position
10 and applied force.

Disclosure of the Invention

 According to the present invention, a manipulator for controlling the position and force of a retained device
15 includes a housing connected to a frame by primary gimbal means permitting pivotal motion of the housing, means to retain the device in a distal end of the housing, and means to apply force in a force plane through a joint in the end of the housing opposite the distal end. Planar force
20 through the joint causes the housing to pivot thereby transferring the planar force into spherical motion and force at the device. In a particular embodiment, the primary gimbal means includes primary gimbal axes which pass through the center of mass of the pivoting components.
25 A method of applying force at the device includes the steps of applying a force in the force plane and transferring the planar force to a pivotal force.

 "Device" as used herein refers to any of a variety of instruments which may be subjected to position and force
30 control. Devices include both tools, such as deburring tools, and components being installed into a larger system.

 According further to the present invention, a force applying means for a manipulator includes an actuator

assembly having a voice coil adapted to apply a force to a housing of the manipulator. In one embodiment, the force applying means includes an actuator assembly having two voice coils, each of the voice coils being aligned along coplanar lateral axes which extend radially from the longitudinal axis of the frame and define the force plane. Each of the voice coils may be energized to direct a force along its axis. The two voice coils are coordinated to generate a force in any direction in the force plane. In a particular embodiment, the actuator assembly includes two pair of voice coils with each pair aligned with one of the lateral axes. This configuration provides a balanced actuator assembly and lower bandwidth requirements on the control system. A method of controlling force on the device includes the steps of determining a force error between a sensed force and a required force, determining the lateral axes components of the force error, and energizing the voice coils to produce the required force.

In some applications, two dimensional control of force and position may not be required. A particular embodiment for this situation includes an actuator assembly having a single voice coil. The voice coil is an arc motor disposed between the housing and the frame and which generates a force in a circular direction. This force is applied directly to the housing.

"Voice coil" as used herein refers to an electromagnetic coil that, when energized by an electric current, produces a magnetic field about the coil. Interaction of this magnetic field with another magnetic field, such as produced by an adjacent magnet, may result in relative force between the coil and magnet.

According further still to the present invention, apparatus for measuring force on the device includes a body

having the retaining means disposed on the distal end of the body, secondary gimbal means joining the body to the housing, and a plurality of force transducers disposed between the housing and the body and about the end of the body opposite the distal end. A force on the device is transferred through the gimbaled body and the force transducers respond to the transferred force. In a particular embodiment, the secondary gimbal means includes secondary gimbal axes which pass through the center of mass of the combined body and device.

According further, apparatus for monitoring position of the device includes two position sensing devices, one disposed adjacent to one pivot of the primary gimbal means and the second disposed adjacent to the other pivot of the primary gimbal means. Movement of the gimbaled housing in any direction away from the longitudinal axis is sensed by the position sensors. The outputs of the two sensors may then be combined to determine the angular or linear position of the device retained in the distal end.

According further still, an apparatus for transferring the planar force between the force applying means and the joint includes a plurality of arms extending between the force applying means and the joint, wherein the arms are stiff along the axis of the arms and compliant in the direction perpendicular to the force plane. The plurality of arms permit both planar linking between the force applying means and the joint and deviations in position of the joint out of the force plane associated with the angular or solid angle motion of the gimbaled housing.

According to a further embodiment of the present invention, a position and force control for the manipulator includes means to determine a position error, means to determine a force error, summing means to sum the errors,

and means to input the summed error into the force applying means. A method of controlling position and force includes the steps of calculating the position and force errors, summing the errors, and inputting the summed error into the
5 force applying means.

A principle feature of the present invention is the kinematic arrangement and method for transferring planar forces into a spherically directed force on a device at a remote position. A primary advantage of this feature is
10 the accuracy in position and force of the device that results from the ability to have essentially direct drive control of position and force on the device. Direct drive minimizes stiction and backlash to thereby improve accuracy. In conventional manipulators, non-direct drive
15 transmissions, such as ball screws or gear trains, create stiction and backlash that reduce accuracy. Additionally, non-direct drive transmissions provide minimal or no passive back driveability. Another advantage of this feature is the ability to control position and force on the
20 device in two dimensions approximating a plane. Although the pivoting motion of the housing results in movement of the device in a spherical direction, since the pivotal movements of the housing are small relative to the longitudinal length of the housing, the spherical motion of
25 the device approximates planar motion for practical applications. As a result, force on the device may be controlled in a direction which, for practical purposes, is normal to the object being worked upon and position may be controlled in a tangential direction. A still further
30 advantage is the simplicity of the control system as a result of the ability to simultaneously control both force and position in any direction in a plane. Simultaneous control of position and force is accomplished by summing

the differences between desired and sensed force and desired and sensed position. The resulting sum is then input to the force applying means to control both the force and position of the device.

5 A feature of a particular embodiment is the gimbaling of the housing at the center of mass of the pivoting components. An advantage of this particular embodiment is the insensitivity of the housing and device to gravitational forces and translational acceleration.
10 Because of this feature, the manipulator may be reoriented with minimal deviations of the device position relative to the frame. The device may also be linearly accelerated without having to actively compensate for inertial forces on the housing and device. Translational motion is typical
15 in robotics applications. Although the balancing of the gimbaled housing will not eliminate deviations resulting from angular acceleration, this type of movement is usually less severe in robotic applications than translational motion.

20 Another feature of this invention is the actuation assembly which uses voice coils to generate force on the housing. In one embodiment, the actuator assembly has only a single voice coil which is directly connected to the housing and generates a force directed in a circular
25 direction. In another embodiment, the actuator assembly has two voice coils aligned with coplanar lateral axes. The pair of voice coils generate a planar force and are connected to the housing via an apparatus that transfers planar force to the gimbaled housing. As a result, the
30 force applying means is inherently back driveable. Further, the connection between the actuation assembly and the process, the connection comprising the web, spider, universal joint and gimbaled housing, provides a back

driveable motion system. An advantage of being passively back driveable is the improved accuracy and stability which results from the low bandwidth control system which may be used to control force on the manipulator. Since the
5 actuation assembly is inherently back driveable, there is a lower bandwidth requirement for a force control feedback loop to control force on the device in response to deviations in the path or object. This permits the bandwidth of the force control system to be less than the
10 resonant frequencies of the robotic arm or numerically controlled machine to which the manipulator is attached. An advantage of the single axis actuation assembly is the improved accuracy and dynamics of the control as a result of the elimination of the transmission between the actuator
15 assembly and the housing. The single voice coil is an arc motor which provides a force in a circular direction that coincides with the circular motion of the end of the pivoting housing. As a result, the actuation assembly is passively backdrivable with zero stiction and backlash.

20 A further feature of this invention is the method and apparatus for measuring force and monitoring position of a device located at a remote position. An advantage of this feature is the ability to measure forces on the device itself and to monitor the position of the device. A
25 further advantage of this feature is that the force measurement and position monitoring does not interfere with the operability of the device. In a particular embodiment, a further feature is the gimbaling of the body at the center of mass of the combined body and device. An
30 advantage of this particular embodiment is the elimination of the need to compensate the force measurements during changes in orientation as a result of the insensitivity of the force measurement apparatus to gravitational or dynamic

forces.

The foregoing and other objects, features and advantages of the present invention become more apparent in light of the following detailed description of the exemplary embodiments thereof, as illustrated in the accompanying drawings.

Brief Description of the Drawings

FIG. 1 is an illustration of a robotics arm including a deburring tool, a control system, and an object to be deburred.

FIG. 2 is a perspective view, partially cut away, of a manipulator in accordance with the present invention.

FIG. 3 is a schematic diagram of the kinematic arrangement of the manipulator.

FIG. 4 is a top view of an actuator assembly, spider and universal joint.

FIG. 5 is a side view, partially cut away, of the actuator assembly spider and universal joint.

FIG. 6 is a side view of a force measurement system for the manipulator, including a secondary gimbal means and a plurality of force transducers.

FIG. 7 is a top view of the force measurement system for the manipulator.

FIG. 8 is a top view of an alternate arrangement for the force measurement system.

FIG. 9 is a side view of a position measurement system for the manipulator.

FIG. 10 is a top view of the position measurement system for the manipulator.

FIG. 11 is a functional block diagram of the manipulator control system showing a force feedback loop and a position feedback control loop.

FIGs. 12a, b, c and d are graphical illustrations of force and position projections.

FIG. 13 is an alternative arrangement for the force measurement system.

5 FIG. 14 is a side view of a single axis manipulator having a voice coil.

FIG. 15 is a front view, partially cut away, of the single axis manipulator.

10 Best Mode for Carrying Out the Invention

FIG. 1 is an illustration of a robotic arm 20 having a deburring tool 22 for performing work upon an object 24. The tool is retained to the arm by a manipulator 26. The deburring tool is moved in a path about the object being worked upon such that the tool maintains contact with the object and has a constant working force directed normal to an edge 28 of the object. The arm is programmed to follow approximately the edge 28 of the object by being moved tangentially to the edge. The manipulator controls the precise positioning of the tool through a control system 30 having a feedback loop for position of the device. In addition, the control system includes a force feedback loop and controls the force between the tool and the object being worked upon.

25 A detailed illustration of the manipulator 26 is shown in FIG. 2. The manipulator has a longitudinal axis 32, a pair of lateral axes 34,36 defining a force plane, a pair of primary gimbal axes 38,40, and a pair of secondary gimbal axes 42,44. The manipulator includes an actuation assembly 46 having a frame 45 attached to the arm 20, a spider 52, a universal joint 54, and a housing 56. The tool 22 is retained within a motor spindle 57 which provides for rotation of the tool.

Although shown in FIGs. 1 and 2 as a deburring tool, the tool is used for illustrative purposes as representative of a manipulated device. The motor spindle is representative of a body disposed within the housing and including a distal end having means to retain the tool.

The actuation assembly includes a first and second pair of voice coils 58,59 disposed along one of the lateral axes and tied together through a web 60. The frame includes two pair of keepers 61, each having a magnet 62 which is engaged with one of the voice coils, and four bearings 63. The actuator assembly in conjunction with the keepers defines means to apply force in the plane defined by the lateral axes. Each of the magnets 62 interacts with the energized voice coils adjacent to it to produce an electromagnetic force on the actuator assembly. The force causes the actuator assembly to move along the lateral axis along which the voice coil is disposed. The energized voice coils in conjunction produce a planar force in the plane defined by the lateral axes. It should be apparent that either the voice coils, as shown, or the keepers could be used as the movable component to drive the actuator assembly. The relative motion between the voice coils and keepers is the driving force in the force applying means. Further, it should be apparent that planar motion and force may be achieved with only two voice coils if desired, one aligned with each of the lateral axes.

As shown in FIG. 3, the bearings 63 are ball transfer units which are in rolling contact with the web. The bearings support the actuator assembly to maintain a spatially constant force plane and prevent the actuator assembly from wearing against the keepers. Ball transfer units are well known in the industry. A commercial source of such items is Interroll Corporation located in

Wilmington, North Carolina.

The actuator assembly transfers force to the housing via the spider 52. The spider, also shown in detail in FIGs. 3-5, includes a hub 68 and a plurality of legs 72 extending radially between the web and the hub. Each of the legs are angled at 45° relative to the adjacent lateral axes to allow engagement of the actuator assembly with the hub without interference from the keepers or other nearby structure while being able to locate the universal joint 54 in the force plane. The hub is engaged with the universal joint to permit transfer of forces in or close to the force plane. The universal joint is one means to permit the housing to be attached directly to the actuator assembly in a manner permitting pivotal motion of the housing. A suggested type of universal joint is a zero backlash universal joint. Such universal joints are commercially available from General Thermodynamics Corporation located in Plymouth, Massachusetts.

The spider illustrated in FIGs. 3-5 is a mechanism for transferring force between the actuation system and the housing with minimal backlash and stiction. Another mechanism which may be used is a conventional linear bearing disposed between the housing and the actuation assembly. A linear bearing, however, may introduce additional backlash and stiction.

The housing 56 is connected to the frame via a primary gimbal means 76 having a primary gimbal ring 79, a first pair of pivots 80 disposed between the primary gimbal ring and the frame, and a second pair of pivots 81 disposed between the primary gimbal ring and the housing (see FIG. 10). The housing 56 includes a sleeve 73, a linkage 74 extending longitudinally from the housing to the universal joint, a clamp 75, and a secondary gimbal means 77.

The primary gimbal means 76 permits pivoting of the housing relative to the frame about the primary gimbal axes 38,40. The first pair of pivots 80 permit the housing to pivot about primary gimbal axis 40 and the second pair of pivots permit the housing to pivot about primary gimbal axis 38. The primary gimbal axes are located at the center of mass of the moving parts of the manipulator, which includes the actuator assembly, spider, universal joint, housing, motor spindle and cutting surface. This location results in the pivoting elements (i.e., the moving parts) being both gravitationally and dynamically balanced. It is suggested, although not necessary, that the primary gimbal means be frictionless, stiction-free, and without radial play. One means of accomplishing this is to use flexural pivots such as those commercially available from Lucas Aerospace located in Utica, New York.

The clamp 75 extends about the motor spindle 57 and engages the secondary gimbal means 77 to retain the motor spindle to the sleeve 73 of the housing. The secondary gimbal means includes a secondary gimbal ring 83, a first pair of pivots 85, and a second pair of pivots 87. The first pair of pivots are disposed between the sleeve and the secondary gimbal ring and permit the motor spindle to pivot about the secondary gimbal axis 44. The second pair of pivots are disposed between the secondary gimbal ring and the clamp and permit the motor spindle to pivot about the secondary gimbal axis 42.

The kinematics of the manipulator in response to forces applied through the actuators is schematically shown in FIG. 3 for a single pair of voice coils and a single primary gimbal axis. Each pair of voice coils is energized together to reinforce each other. The force generated along the lateral axis is transferred to the universal

joint by the legs of the spider. The universal joint moves in response to the force applied and thereby causes the housing to pivot about the gimbal. The legs of the spider are stiff in the direction of the lateral axis in order to transfer the forces, but are compliant in the direction normal to the force plane. This compliance permits the universal joint to move out of the force plane as the housing pivots and the universal joint moves through an arc.

Another feature of the legs of the spider is illustrated in FIG. 5. During installation of the spider into the frame, the legs of the spider are initially deformed to introduce a bias and produce a longitudinally directed force F on the actuator assembly. This longitudinal force F pushes the actuator assembly against the bearings to ensure contact with the bearings. Thus, the actuator assembly rides on the bearings even if the manipulator is placed in positions where gravitational forces urge the actuator assembly away from the bearings.

A force measurement system 78 is illustrated in FIGS. 6 and 7. The force measurement system includes a plurality of force transducers 82 disposed on a transducer ring 84 surrounding the motor spindle 57, a corresponding plurality of flexures 86 extending between the force transducers and an extension 88 of the housing 56, and the control system 30. As with the primary gimbal means, the secondary gimbal is located at the center of mass of the transducer ring 84, clamp 75, secondary gimbal ring 83 motor spindle 57 and tool 22 such that the combined components pivoted relative to the housing by the secondary gimbal means are gravitationally and dynamically balanced. The control system includes means 94 to correlate the force signals from the transducers to determine the force on the tool in

the working plane.

Forces on the tool urge the motor spindle to pivot about the secondary gimbal means. This force is resisted by the flexures disposed between the force transducers and the housing. Since each of the force transducers is disposed between one of the flexures and the motor spindle, each transducer outputs a signal corresponding to the force in the direction of the flexure. As shown in FIG. 7, each flexure is stiff in the lateral direction through which it extends, but is flexible in the direction perpendicular to that lateral direction. This limits each pair of transducers to measuring primarily the force along one lateral axis. The outputs of the plurality of transducers are sent to the control system to determine the force in the working plane. Pairs of transducers are used in a differential fashion to amplify the force signal and reduce the noise common to both the transducers. Using two pair with oppositely directed outputs permits the two signals to be subtracted to thereby add the force signal (because of the opposite signs of each signal) and subtract out the common noise.

The plurality of force transducers and flexures is disclosed as one means of measuring force in a plane. An alternative means 96 is shown in FIG. 8. The alternative means includes two pairs of gap probes 98,102 retained in the housing, each pair disposed along a lateral axis 104,106, and a plurality of springs 108. Forces on the tool that urge the motor spindle to pivot about the secondary gimbal means would be resisted by the springs which act as resilient members. The resulting movement of the spindle relative to the gap probes would be related to the force on the tool. An advantage of this alternative means 96 over the force measurement system disclosed in

FIGs. 6 and 7 is the elimination of contact between the force measuring devices, i.e. the force transducers in FIGs. 6 and 7 or the gap probes in FIG. 8, and the item to which the force is being applied, i.e. the motor spindle in
5 FIGs. 6 to 8. Eliminating this contact may reduce wear and result in a more robust force measurement system.

Another alternative means 109 of measuring force in a plane is shown in FIG. 13. This embodiment includes a plurality of strain gages 110 mounted on legs 111 extending
10 between the housing and the spindle. The strain gages respond to strain within the legs. The strain measurement is proportional to the force on the device.

A position monitoring system 112 is disclosed in FIGs. 9 and 10. The position monitoring system includes the
15 control system 30 and two pair of gap sensing probes 114, 116. The control system includes means 118 to correlate the position signals from the probes to determine the position of the tool in the working plane. Each pair of probes is adjacent with one of the gimbal axes. The
20 first pair of probes 114 is disposed between the primary gimbal ring and the frame. The second pair of probes 116 is disposed between the primary gimbal ring and the housing. The pairs of probes are responsive to any pivotal motion of the housing. Both pairs of probe signals are
25 input to the control system where the position correlation means determines the position of the cutting surface in the force plane. A suggested type of gap probe is an eddy current sensor such as commercially available from Kaman Instrumentation Corporation located in Colorado Springs,
30 Colorado.

During operation, the robot arm provides gross positioning of the tool relative to the object to be worked upon. In essence, the robot arm gets the tool close to the

object. The manipulator is controlled by the control system to direct the tool force along an axis normal to the object and to position the tool along an axis tangential to the object. The control system includes feedback loops for
5 both force and position to provide means to correct either force or position, or both if necessary.

The force feedback loop 122 and the position feedback loop 124 are shown in FIG. 11 and illustrated graphically in FIGs. 12a, b, c and d. In the force feedback loop, the
10 transducer signals 125 are first input to the means 94 to determine the measured force F_M and to project the measured force F_M onto the normal axis to produce $F_{M,N}$. Next the normal axis projection $F_{M,N}$ signal 126 is compared 128 with a predetermined set point force 132 (F_d) to determine a
15 force error signal 134 (F_e). The force error signal is then input to a compensator 136 to filter the force error signal F_e . The filtered error signal 137 is then input to means 138 to project the force error F_e onto the pair of lateral axes M_1 and M_2 .

20 The position feedback loop 124 is similar to the force feedback loop and includes inputting the probe signals 140 to the means 118 to determine the measured position P_M and to project the measured position P_M onto the tangential axis to produce $P_{M,T}$. Next the tangential axis projection
25 signal 144 is compared with a predetermined position set point 146 (P_d) to determine a position error signal 148 (P_e). The position error signal is then input to compensator 152 to filter the position error signal P_e . The filtered error signal 153 is then input to means 154 to
30 project the position error signal P_e onto the pair of lateral axes M_1 and M_2 .

The projected force error signal 155, shown as F_{M1} and F_{M2} in FIG. 12b, and the projected position error signal 156

shown as P_{M1} and P_{M2} in FIG. 12d, are then summed. The summed output 158 determines the magnitude of the control signal sent to the first and second pair of voice coils. The actuator assembly moves in response to the control
5 signal and thereby causes the housing to pivot and move the tool toward the desired position P_d and toward the desired force F_d .

The control system described above is a means to control force in the normal direction and position in the
10 tangential direction, a hybrid force and position controller. In some instances, however, it may be preferable to control position in both the normal and tangential direction. One such situation occurs prior to engagement of the tool and surface to be operated on. In
15 order to transition the device through the working envelope, i.e. bring the tool from its initial position to a position in which it is engaged with the object, position of the device may be controlled along both the normal and tangential axis. Force control is not necessary in this
20 situation and the control system is essentially a two-dimensional position controller. The motion may be controlled to permit the tool to smoothly transition through the envelope. This type of transition may avoid damaging impact between the tool and the object.

25 In some applications, two-dimensional control of force and position may not be required. An alternate embodiment that satisfies the need for one-dimensional control is illustrated in FIGS. 14 and 15. This manipulator 200 is retained within a frame 202 of the arm 204 and includes an
30 actuation assembly 206 and a housing 208. The housing 208 is connected to the frame 202 by a pivot 210 disposed therebetween. The frame 202 includes a pair of stops 211 which limit the pivotal motion of the housing 208. A

cutting tool 212 is retained within a motor spindle 214 disposed within the housing 208. The manipulator 200 has a longitudinal axis 216 and a pivot axis 218.

5 The actuation assembly 206 includes a single voice coil 220. The actuation assembly is an arc motor having a magnetic core 222 directly attached to the frame 202 and the voice coil 220 disposed about the core 222 and attached to the housing 208. The core 222 has an arcuate shape such that, upon energizing of the wire coil 224, the core 222
10 causes the wire coil 224 to move with a circular motion having a center of radius coinciding with the pivot axis 218. Since the wire coil 224 is directly connected to the housing 208, motion of the wire coil 224 results in motion of the cutting tool 212 along a circular path 230. The
15 circular path 230 also has a center of radius which coincides with the pivot axis 218. Although described as having an arcuate core, it should be noted that either the core or the voice coil, or both as desired, may be curved.

A position sensor 232 is connected to the frame 202
20 and adjacent to the housing 208. The position sensor 232, shown in FIG. 14 as a gap sensor, is positioned to monitor the pivotal movement of the housing 208. If needed, a force sensing system may be disposed between the housing 208 and the spindle in a manner similar to that shown in
25 FIGs. 6-7 or as shown in FIG. 8.

The embodiment shown in FIGs. 14 and 15 is kinematically a one-dimensional version of the embodiment shown in FIGs. 1-11. This limits the manipulator to position and force control in one direction and to back-
30 driveability in only one direction. A benefit of the one-dimensional embodiment is that the actuation assembly is a direct drive mechanism. There are no transmissions between the actuation assembly and the housing to introduce

stiction and backlash into the system.

Although the invention is described in FIGs. 1-11 as a manipulator for use with a robotic arm, it should be understood that the manipulator may be used with other
5 types of programmable position controllers; such as numerically controlled machines.

Although the invention has been shown and described with respect with exemplary embodiments thereof, it should be understood by those skilled in the art that various
10 changes, omissions, and additions may be made thereto, without departing from the spirit and scope of the invention.

Claims

What is claimed is:

1. A manipulator for positioning a device relative to an object to be worked upon by the device, wherein the manipulator provides a predetermined engagement force between the device and the object, the manipulator including:

a frame having a longitudinal axis;

a housing connected to the frame by a primary gimbal means, the housing including a distal end, an end opposite the distal end, and means to retain the device in a relationship permitting work to be performed on the object, the retaining means disposed on the distal end of the housing;

a joint disposed on the end of the housing opposite the distal end, the joint permitting pivotal motion of the housing about the gimbal; and

force applying means including an actuator assembly adapted to apply a force in a plane passing through the joint, the force applying means causing the housing to pivot about the gimbal such that the device is positioned relative to the object.

2. The manipulator according to Claim 1, wherein the force applying means includes a pair of keepers, the actuator assembly including a first voice coil aligned along a first lateral axis and a second voice coil aligned along a second lateral axis, the first and second lateral axis being coplanar wherein the plane is perpendicular to the longitudinal axis and defines a force plane, and wherein the first voice coil is adapted to apply a force to the housing along the direction of the first lateral axis and wherein the second voice coil is adapted to apply a

force to the housing along the direction of the second lateral axis.

5 3. The manipulator according to Claim 1, further including a plurality of legs extending between the actuator assembly and the joint, the legs being fixedly engaged with the joint, wherein the legs are stiff along the axis of the legs to transfer force from the force applying means to the joint, and wherein the legs are compliant in a direction perpendicular to the force plane to permit motion of legs out of the force plane.

10 4. The manipulator according to Claim 1, wherein the housing, the joint and the actuator assembly comprise a plurality of pivoting components, wherein the primary gimbal means includes first and second primary gimbal axes which pass through the center of mass of the plurality of pivoting components such that the pivoting plurality of pivoting components are gravitationally and dynamically balanced.

15 5. The manipulator according to Claim 21, the frame further including a pair of keepers, the actuator assembly further including a first voice coil aligned along a first lateral axis, a second voice coil aligned along a second lateral axis, the first and second lateral axis being coplanar wherein the plane is perpendicular to the longitudinal axis and defines a first plane, and wherein the first voice coil is adapted to apply a force to the housing along the direction of the first lateral axis and
20
25 wherein the second voice coil is adapted to apply a force to the housing in the direction of the second lateral axis.

5 6. The manipulator according to Claim 5, further including a plurality of legs extending between the actuator assembly and the joint, the legs being fixedly engaged with the joint, wherein the legs are stiff along the axis of the legs to transfer force from the force applying means to the joint, and wherein the legs are compliant in a direction perpendicular to the force plane to permit motion of the legs out of the force plane.

10 7. The manipulator according to Claim 6, wherein the housing, the joint and the actuator assembly comprise a plurality of pivoting components, wherein the primary gimbal means includes first and second primary gimbal axes which pass through the center of mass of the plurality of pivoting components such that the pivoting plurality of
15 pivoting components are gravitationally and dynamically balanced.

20 8. An apparatus for measuring force on a device, the apparatus having a longitudinal axis and including a housing, a body, and a plurality of transducers, the body connected to the housing by a pivot means, the body including a distal end with means for receiving the device and an end opposite the distal end, the plurality of transducers disposed between the housing and the body at the end opposite the distal end, wherein a force on the
25 device causes the body to pivot about the pivot means whereby the transducers respond to the pivoting motion.

30 9. The apparatus according to Claim 8, wherein the plurality of transducers include load cells and the apparatus further includes a plurality of flexures disposed between the transducers and the housing, each of the

plurality of flexures extending along a lateral axis and being rigid in the direction of the lateral axis and compliant along an axis coplanar with and perpendicular to the lateral axis.

5 10. The apparatus according to Claim 8, wherein the
plurality of transducers include gap sensors adapted to
detect relative movement between the housing and the
opposite end of the body, and wherein the device further
10 includes a plurality of resilient members disposed between
the body and the housing and adapted to resist motion of
the body relative to the housing.

15 11. An apparatus for monitoring position of a device, the
apparatus having a longitudinal axis and including a frame,
a housing, and a plurality of position probes, the housing
being connected to the frame by a gimbal means, the gimbal
means including a gimbal ring disposed between the frame
and the housing, the housing including a distal end with
means for receiving the device, the plurality of position
20 probes including a first probe disposed between the frame
and the gimbal ring and a second probe disposed between the
gimbal ring and the housing, the probes being in a plane
perpendicular to the longitudinal axis, wherein movement of
the device causes the housing to pivot about the gimbal
whereby the probes respond to the pivoting motion.

25 12. The apparatus according to Claim 11, wherein the
plurality of probes include gap probes adapted to respond
to changes in spacing between objects, and wherein the
first probe responds to the variation in spacing between
the frame and the gimbal ring and the second probe responds
30 to variations in spacing between the gimbal ring and the

housing.

5 13. An apparatus for transferring forces between an actuator assembly disposed within a frame and adapted to generate planar force and a housing which pivots in response to the force applied, the housing pivoting about a point having a fixed relationship relative to the frame, the housing connected to the actuator assembly by a joint adapted to receive the forces, the joint moving out of the force plane during pivotal movement of the housing, the apparatus including a plurality of legs extending between 10 the actuator assembly and the joint, wherein the legs are stiff along the direction of the force plane to transfer force from the actuator assembly to the joint, and wherein the legs are compliant in a direction perpendicular to the force plane to permit motion of the joint out of the force 15 plane.

20 14. The apparatus according to Claim 13, wherein the legs are initially biased during installation to produce a maintaining force on the actuator assembly to locate the actuator assembly relative to the frame and thereby define the force plane.

25 15. The manipulator according to Claim 2, further including a plurality of legs extending between the actuator assembly and the joint, wherein the legs are stiff along the axis of the legs to transfer force from the force applying means to the joint, and wherein the legs are compliant in a direction perpendicular to the force plane to permit motion of the joint out of the force plane, wherein the housing, the joint and the actuator assembly 30 comprise a plurality of pivoting components, wherein the

primary gimbal means includes first and second primary gimbal axes which pass through the center of mass of the plurality of pivoting components such that the pivoting plurality of pivoting components are gravitationally and dynamically balanced, further including an apparatus for measuring force on the device, the force measuring apparatus having a body disposed within the housing and a plurality of transducers, the body connected to the housing by a secondary gimbal means, the body including the distal end with means for receiving the device and an end opposite the distal end, the plurality of transducers disposed between the housing and the body at the end opposite the distal end, the transducers being in a plane perpendicular to the longitudinal axis, wherein a force on the device urges the body to pivot about the secondary gimbal means whereby the transducers respond to the pivoting motion, and further including an apparatus for monitoring position of a device, the position monitoring apparatus having a plurality of position probes, the primary gimbal means including a gimbal ring disposed between the frame and the housing, the plurality of position probes including a first probe disposed between the frame and the gimbal ring and a second probe disposed between the gimbal ring and the housing, the probes being in a plane perpendicular to the longitudinal axis, wherein movement of the device causes the housing to pivot about the primary gimbal means whereby the probes respond to the pivoting motion.

16. A position and force control for a manipulator, the manipulator including force applying means and a device to be manipulated, the control including:

means to measure force F_m on the device;

means to calculate the force error F_e between the

measured force F_M and a desired force F_d ;
means to measure position P_M of the device;
means to calculate the position error P_e between the
measured position P_M a desired position P_d ;
5 summing means to sum the force error F_e and the
position error P_e to produce a summed error; and
 means to input the summed error to the force applying
means.

10 17. A method of controlling position and force for a
manipulator, the manipulator including force applying means
and a device to be manipulated, the method including:
 measuring force F_M on the device;
 calculating the force error F_e between the measured
force F_M and a desired force F_d ;
15 measuring position P_M of the device;
 calculating the position error P_e between the measured
position P_M and the desired position P_d ;
 summing the force error F_e and the position error P_e
to produce a summed error; and
20 inputting the summed error to the force applying
means.

18. A method for positioning a device relative to an object to be worked upon using a manipulator, the manipulator including a frame having a longitudinal axis, a housing gimbaled to the frame, and force applying means adapted to apply a force to the joint, the housing including a distal end, an end opposite the distal end, and means to retain the device in a relationship permitting work to be performed on the object, the retaining means disposed on the distal end of the housing, a joint connecting the force applying means and the end of the housing opposite the distal end, the joint permitting pivotal motion of the housing about the gimbal, the method including the steps of:

applying a force in the plane through the joint; and transferring the planar force to a pivotal force such that pivoting motion of the housing occurs and the distal end of the housing is positioned relative to the object.

19. The method according to Claim 18, wherein the force applying means further includes two pairs of keepers and an actuator assembly, wherein the actuator assembly further includes a first voice coil aligned along a first lateral axis, a second pair of voice coils aligned along a second lateral axis and on opposite sides of the housing, the first and second lateral axis being coplanar wherein the plane is perpendicular to the longitudinal axis, and wherein the first voice coil is adapted to apply a force to the housing in the direction of the first lateral axis and wherein the second voice coil is adapted to apply a force to the housing in the direction of the second lateral axis, and wherein the method further includes the steps of:

determining the position required;
determining the first lateral axis component of the

position required;

determining the second lateral axis component of the position required;

5 applying an electrical current to the first voice coil to cause motion of the first voice coil corresponding to the first lateral axis component; and

 applying a current to the second pair of voice coils to cause motion of the second voice coil corresponding to the second lateral axis component.

10 20. The method according to Claim 19, wherein the manipulator further includes a body and a plurality of transducers, the body connected to the housing by a secondary gimbal means and including the distal end and an end opposite the distal end, the plurality of transducers
15 disposed between the housing and the body at the end of the body opposite the distal end, the transducers being in a plane perpendicular to the longitudinal axis, and wherein a force on the device urges the body to pivot about the secondary gimbal means whereby the transducers respond to
20 the force, and wherein the method further includes the steps of:

 measuring the force F_M on the device in a plane perpendicular to the longitudinal axis;

25 determining the difference between the desired force F_d and the measured force F_M to produce a force error F_e ;

 determining the first lateral axis component F_{M1} of the force error F_e ;

 determining the second lateral axis component F_{M2} of the force error F_e ;

30 applying an electrical current to the voice coil corresponding to the first lateral axis component F_{M1} of the force error F_e ; and

applying an electrical current to the second voice coil corresponding to the second lateral axis component F_{M2} of the force error F_e .

5 21. A manipulator for positioning a device relative to an object to be worked upon, the manipulator including a longitudinal axis, a frame, a housing, and force applying means, the housing including means to receive the device and being movable relative to the frame, the force applying means including an actuator assembly having a voice coil
10 adapted to apply a force to the housing such that the housing moves relative to the frame.

15 22. The manipulator according to Claim 21, wherein the housing is disposed in pivotal relationship to the frame by a pivot means, wherein the voice coil includes an arc motor disposed between a first end of the housing and the frame, the arc motor providing force on the first end of the housing urging the first end to move in a circular direction and the housing to pivot relative to the frame.

20 23. The manipulator according to Claim 22, wherein the pivot means includes a pivot axis that passes through the center of mass of the moving members including the coil, spindle, device and housing.

25 24. A method for positioning a device relative to an object to be worked upon using a manipulator, the manipulator including a frame having a longitudinal axis, a housing disposed in a pivotal relationship to the frame, and force applying means adapted to apply a force to the housing, the housing including a distal end, an end opposite the distal end, and means to retain the device in

a relationship permitting work to be performed on the object, the retaining means disposed on the distal end of the housing, the force applying means including an arc motor disposed between the housing and the frame, the arc motor adapted to generate a force in a circular direction between the frame and housing, the method including the steps of:

determining the desired position of the device; and energizing the arc motor such that the housing pivots relative to the frame and the device is positioned relative to the object.

25. The apparatus according to Claim 8, wherein the plurality of transducers include strain gages and the apparatus further includes a plurality of legs extending between the body and the housing, and wherein the strain gages are disposed on the legs.

26. The control according to Claim 16, wherein the means to calculate force error F_e onto the axis of the desired force F_d , wherein the means to calculate position error P_e includes means to project the measured position P_M on to the axis of the desired position P_d , and further including means to project the force error F_e and the position error P_e onto the axes of the force applying means.

27. The method according to Claim 17, further including the steps of projecting the measured force F_M onto the axis of the desired force F_d , projecting the measured position P_M onto the axis of the desired position P_d , and projecting the force error F_e and the position error P_e onto the axes of the force applying means.

fig. 1

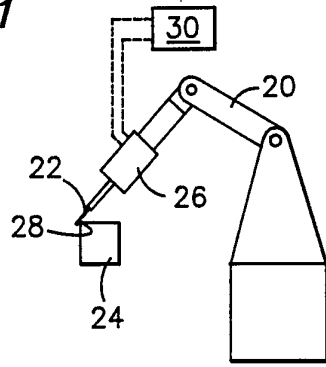


fig. 3

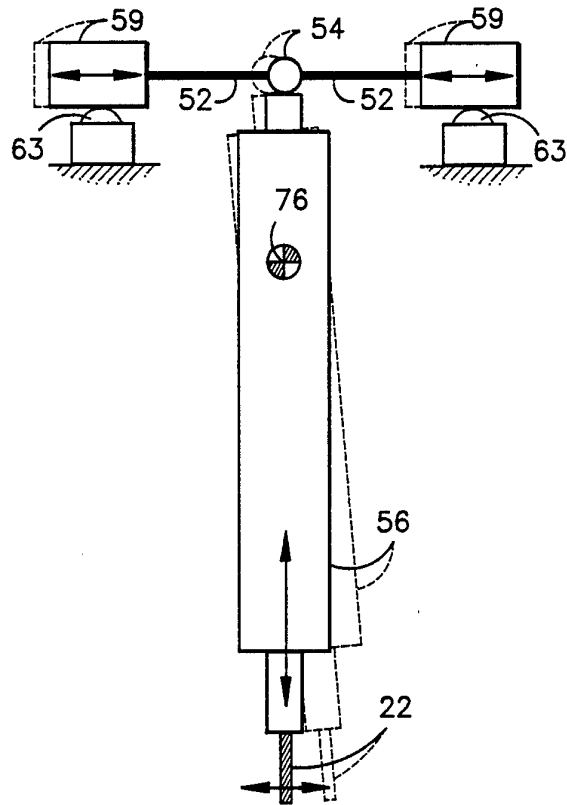
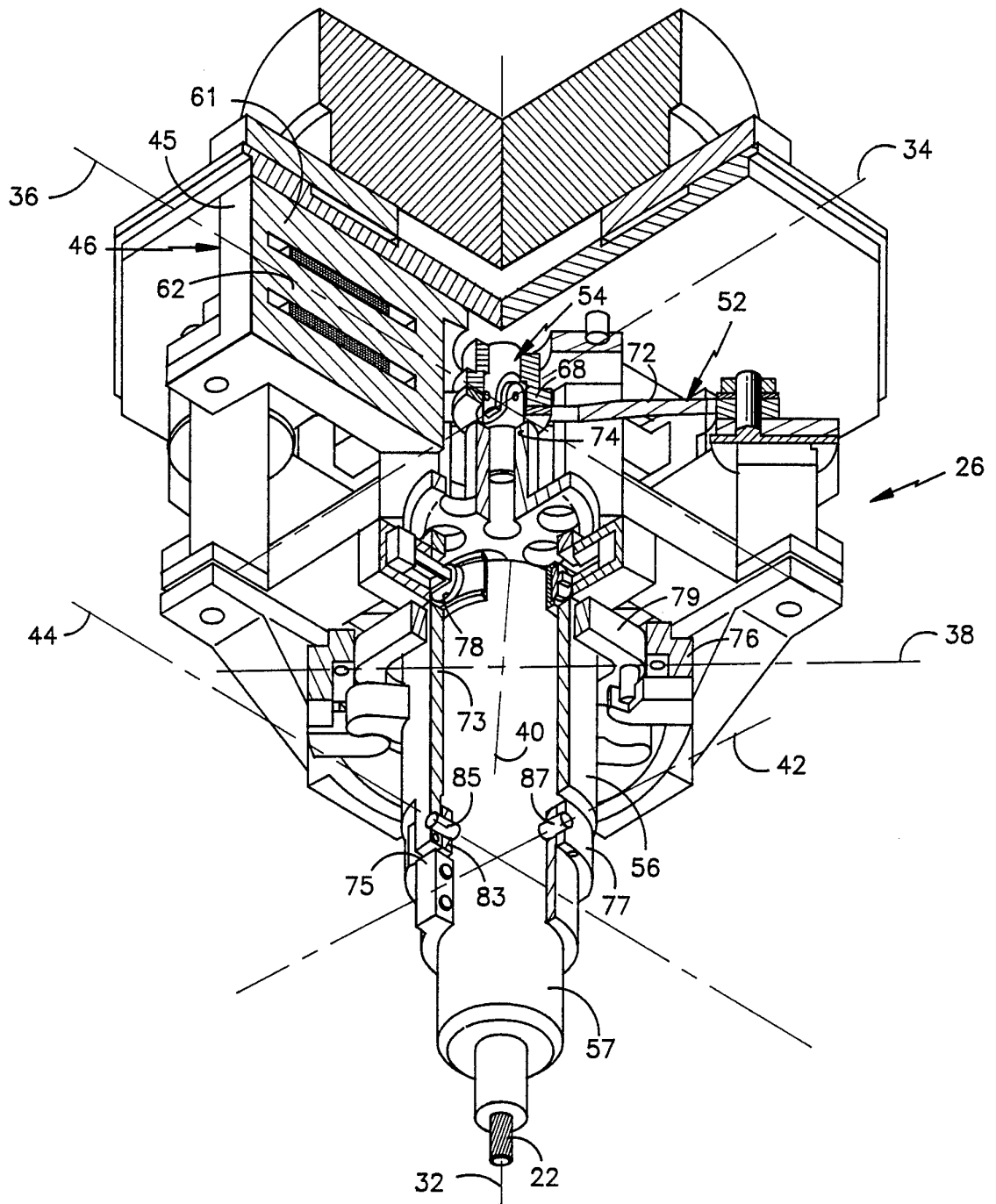


fig.2



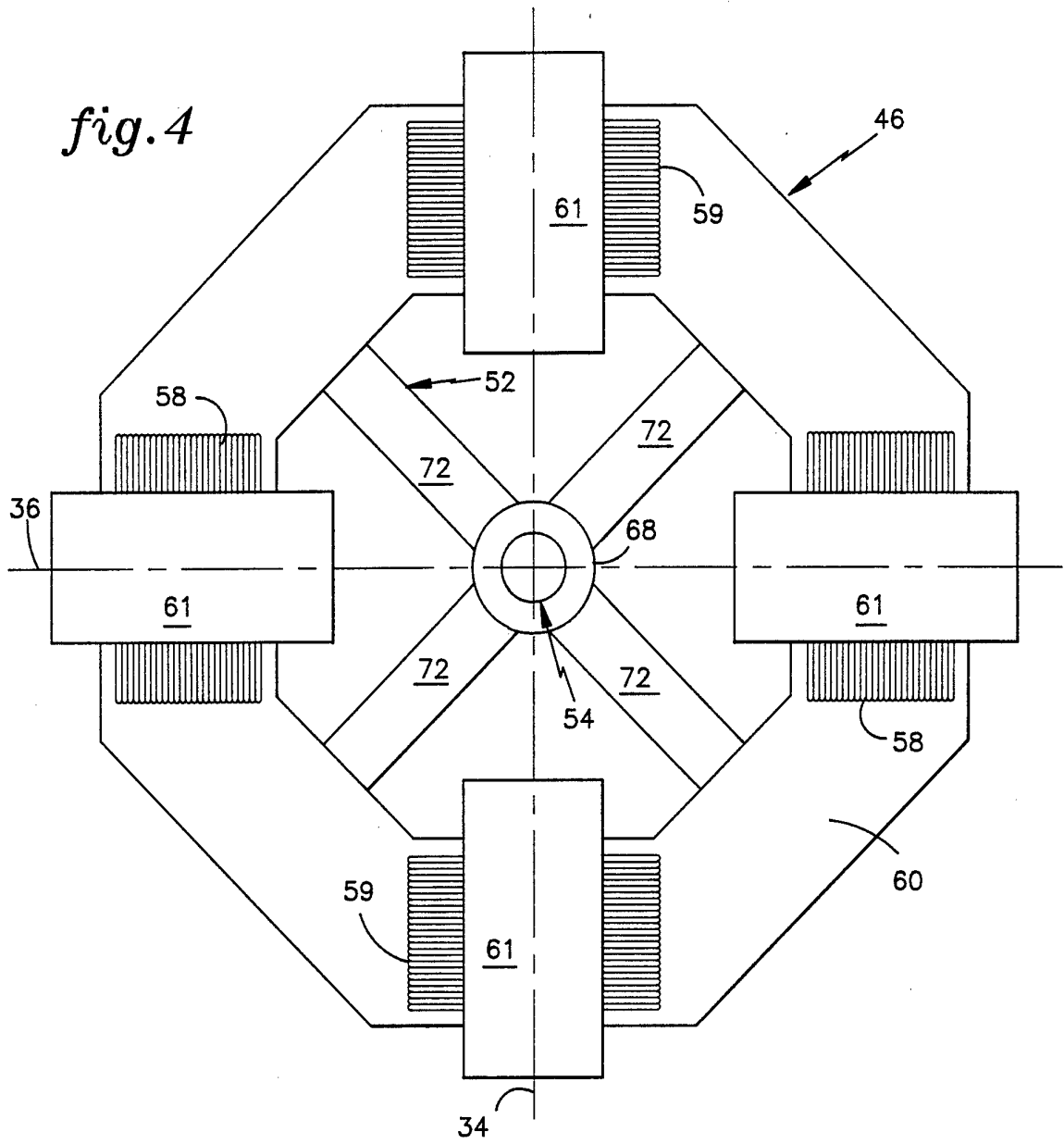


fig. 5

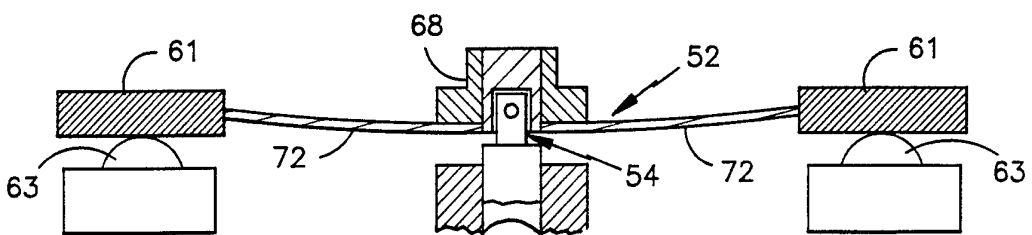


fig. 6

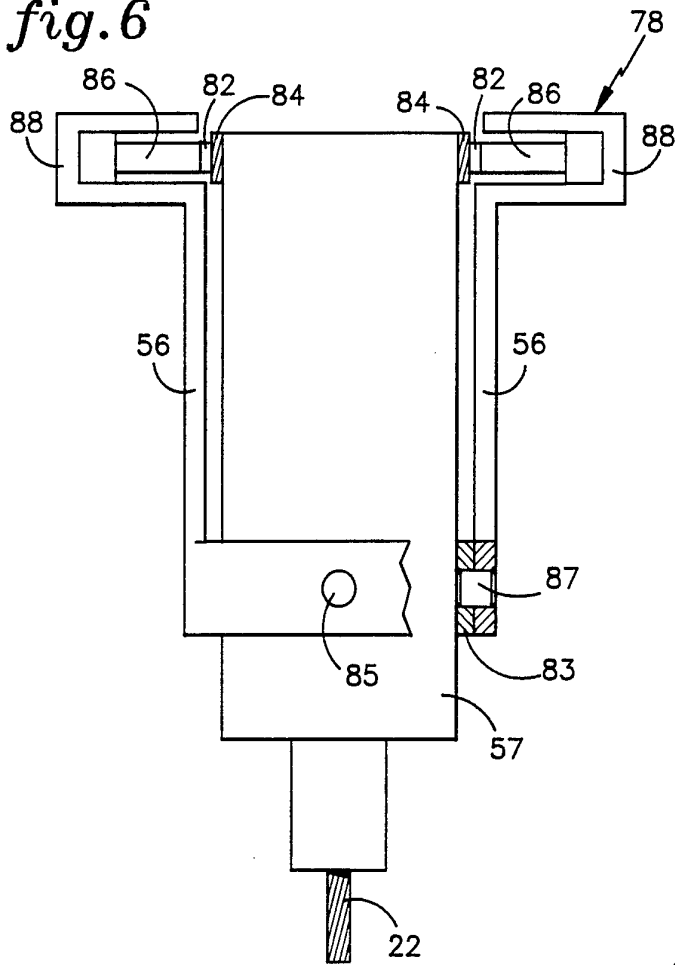


fig. 8

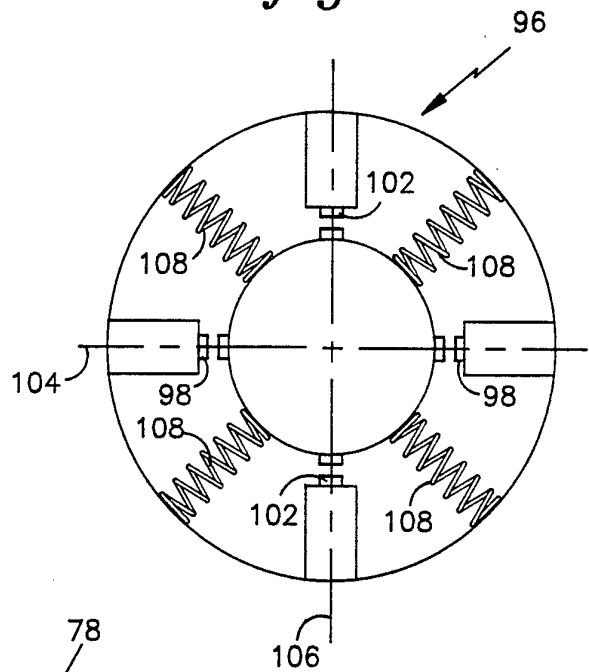


fig. 7

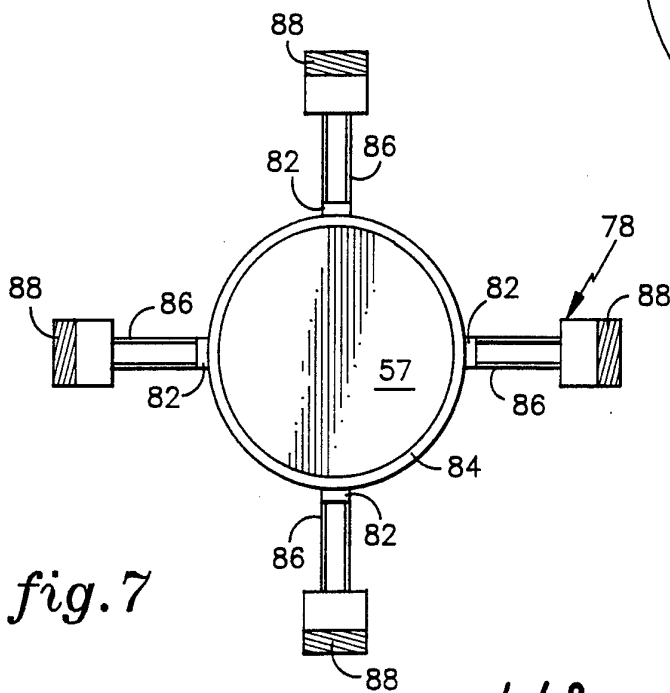


fig. 9

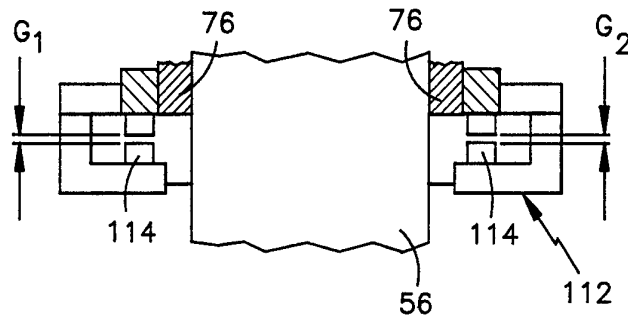


fig. 10

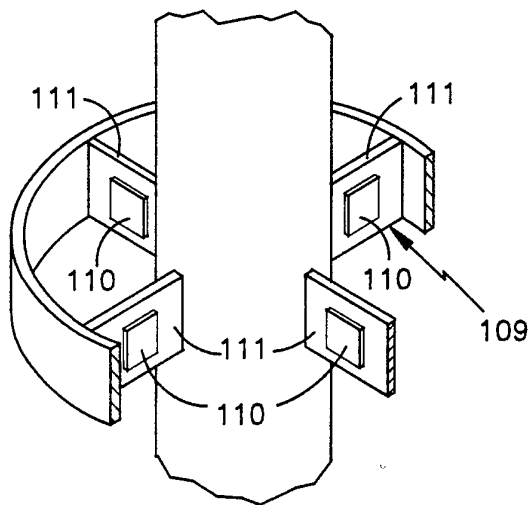
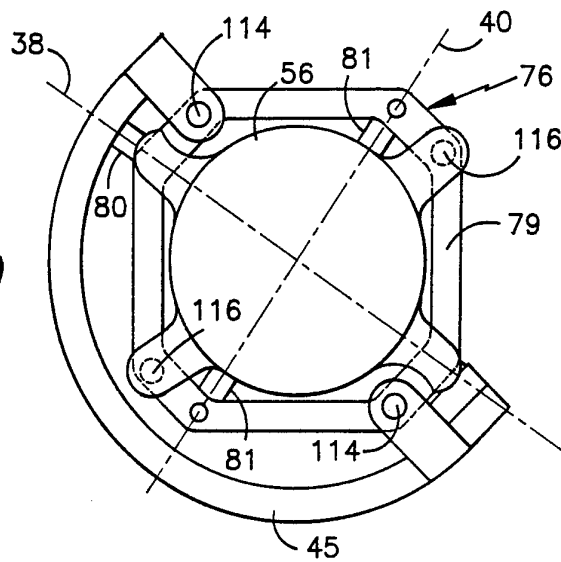


fig. 13

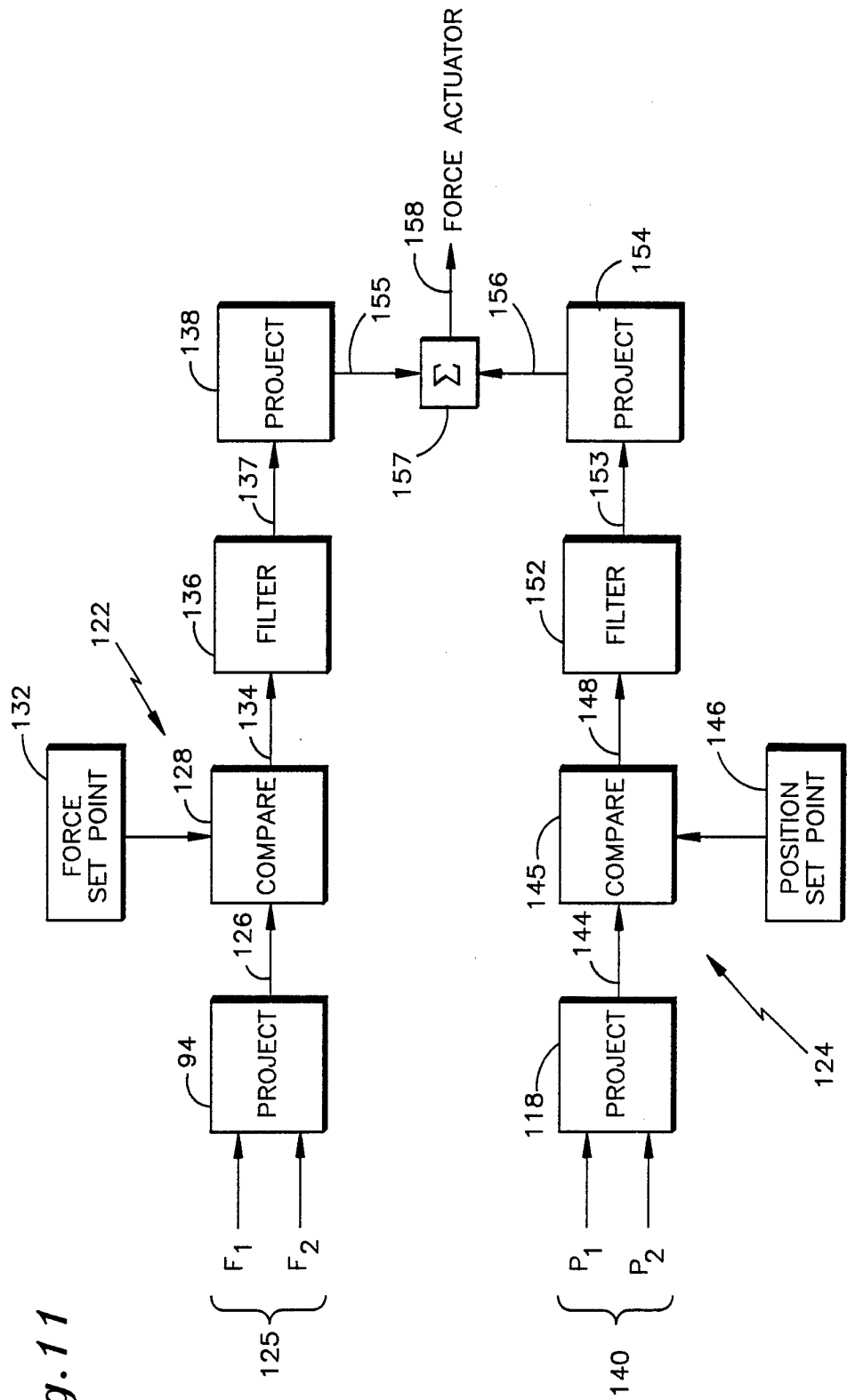


fig. 11

fig. 12A

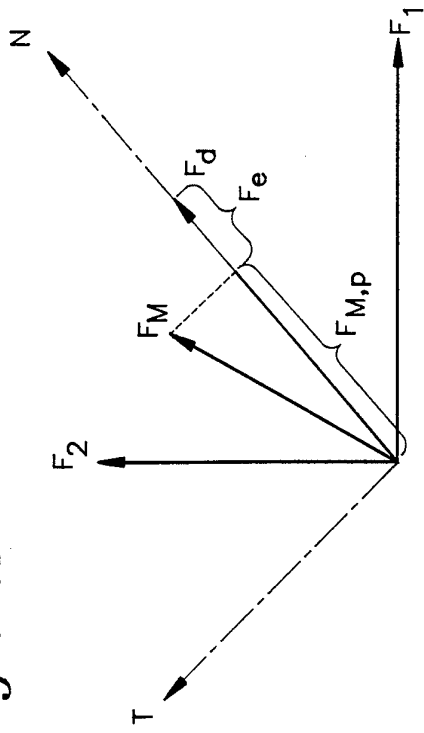


fig. 12B

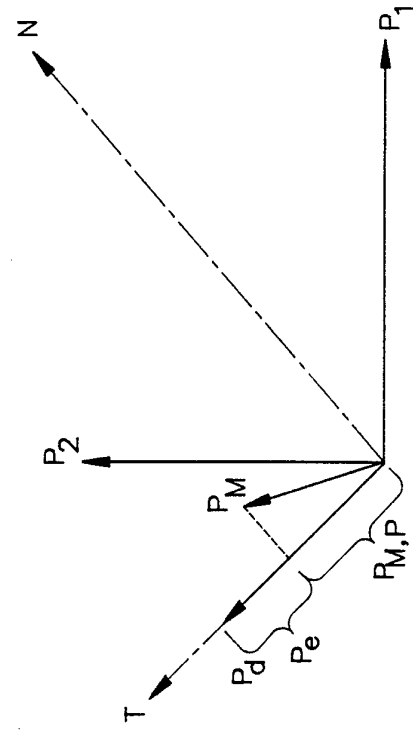
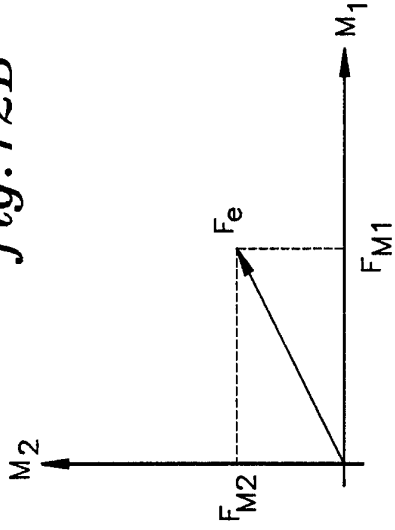


fig. 12C

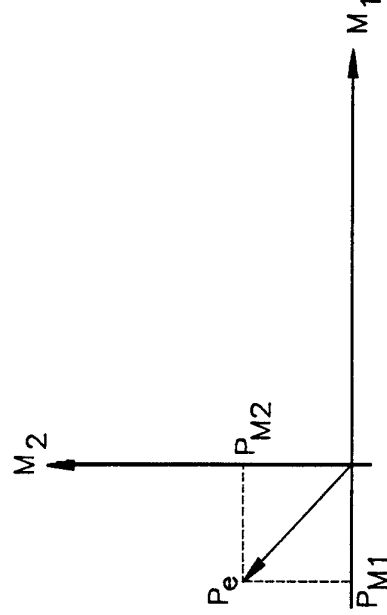


fig. 12D

fig. 14

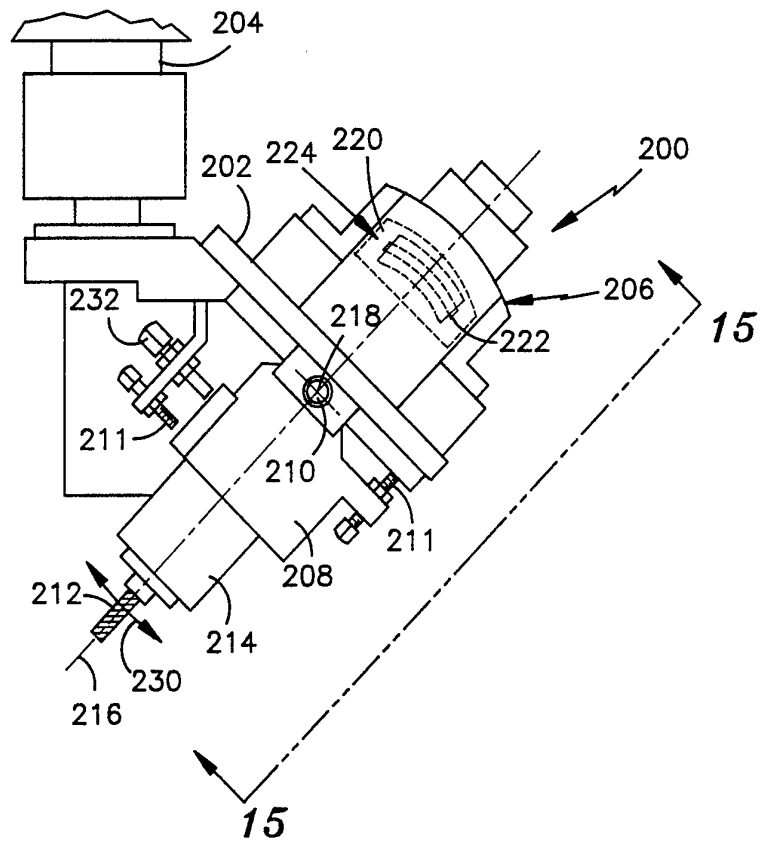


fig. 15

